

## **Atom Wave Interferometers**

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**ONR program officer: Dr. Hersch Pilloff**

### **Long-term research objective:**

Matter wave interferometers, in which de Broglie waves are coherently split and then recombined to produce interference fringes, have opened exciting new possibilities for precision and fundamental measurements with complex particles. The aim of our research program is to extend the ideas and techniques of atom optics and atom interferometry which underlie atom interferometers, to use these devices to make qualitatively new and/or more precise measurements in atomic physics, and to perform fundamental experiments in quantum mechanics based on our ability to measure interactions that displace the de Broglie wave phase or change the quantum coherence of the beams (reducing the amplitude of the interference pattern).

### **S&T objectives**

To develop the techniques of atom optics and atom interferometers, and to find new applications in many scientific and technical arenas. We have pioneered applications in three major areas: precision measurements in atomic physics, atom interferometric inertial sensors, and investigations of fundamental quantum mechanical principles.

### **Approach:**

Our transverse Mach-Zehnder interferometer for atoms & molecules uses three nanofabricated transmission gratings, and generates a "white-fringe" (i.e. insensitive to momentum spread in the beam) interference pattern. Its most unique feature is a spatial separation and isolation of the two interfering beam paths, permitting the application of an interaction to only one of the two paths. We have recently constructed a novel interferometer in which the two interfering paths are separated in longitudinal momentum space. It is ideally suited to the study of interactions that change the kinetic or potential energy of an atom, leading to time-dependent superpositions of states with different total energies.

### **S&T completed:**

During the past year, we have concluded a series of experiments involving longitudinal coherences—intrinsically time dependant superpositions of longitudinal momentum states in an atomic beam. This work has been reported in a series of papers which detail: the ability to

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manipulate and detect simple longitudinal coherences in an atomic beam in a manner analogous to spin-echo phenomena [1], the resolution of a long standing controversy about the correct description of the quantum state of an atomic beam via a search for any inherent longitudinal coherences in our beam source [3], a full measurement of the non-trivial quantum state of a modulated atomic beam [4], and a simple theoretical reformulation of atomic beam resonance which correctly accounts for the quantum nature of atomic motion [2].

We have also nearly completed a series of substantial improvements to our interferometer including: transition to a larger and more flexible vacuum chamber, upgrade of our beam source for substantially improved atom flux, and new inertial stabilization design resulting in a threefold decrease in vibrational noise. We have also incorporated second-generation 100nm period gratings fabricated at the MIT Microsystems Technology Laboratory using the new Achromatic Interference Lithography technique. With these improvements we have been able to observe record 10% contrast interference fringes (previously saw 3%) using 100nm period gratings.

#### **Impact/Navy Relevance:**

A fully quantum treatment of center of mass motion is the essential formalism for the new fields of atom optics and atom interferometry. A quantum characterization of a particle beam's quantum mechanical and statistical properties requires a scheme for determining its density matrix (or equivalently the Wigner function). While tomographic techniques adapted from Magnetic Resonance Imaging (MRI) and optics are useful for measuring a beam's transverse density matrix, they are impractical in the longitudinal case due to the additional difficulty of a time-dependent density matrix, and the complicated mathematics needed to reconstruct the density matrix from measured data. Using our more general technique based on Fourier transforms rather than the inverse Radon transformation, we were the first to measure the longitudinal density matrix of a matter-wave beam.

#### **Planned research efforts:**

We shall soon measure the loss of quantum coherence due to scattering of multiple photons. The interferometer itself is now working reliably, and the necessary laser system has been put in place. This experiment will extend our previous work on quantum decoherence, which demonstrated the loss of interference as successively better "which path" information was gathered. The new experiment will explore net decoherence caused by multiple scattering events, each of which provide little which-path information.

#### **Other sponsored science & technology:**

New Developments in Atom Interferometry. Army Research Office. \$240,000, 8/1/98-7/31/01.

Matter Wave Interferometry with Separated Beams. Army Research Office (AASERT). \$90,000, 6/1/97-5/31/00.

Basic Research in Electronics. Joint Services Electronics Program. \$72,650, 11/1/97 to 10/31/99.

Ionic, Atomic and Molecular Physics. Nat'l Science Foundation. \$838,000, 6/1/99 to 5/31/02.

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### **Productivity:**

#### **Technology Transfer:**

Our demonstration of the inertial sensing capabilities of atom interferometers continues to garner widespread interest both within the scientific community where it is hoped such devices will eventually lead to tests of general relativity, and in the military where atom interferometers may one day replace laser gyroscopes in some inertial navigation systems. Our grating fabrication efforts in collaboration with Prof. Henry Smith at MIT's Microsystems Technology Laboratory are helping to test the large scale reproducibility and feature-size limits of UV lithography.

#### **Journal publications:**

Velocity Rephased Longitudinal Momentum Coherences with Differentially Detuned Separated Oscillatory Fields, Edward T. Smith, Al-Amin Dhirani, David A. Kokorowski, Richard A. Rubenstein, Tony D. Roberts, Huan Yao and David E. Pritchard, Phys. Rev. Lett., **81**, 1996-1999, (1998).

Longitudinal Atom Optics Using Localized Oscillating Fields: A Fully Quantum Mechanical Treatment, David E. Pritchard, Richard A. Rubenstein, Al-Amin Dhirani, David A. Kokorowski, Edward T. Smith, Troy D. Hammond, and Bernt Rohwedder, Phys. Rev. A, **59**, 4641-4652, (1999).

Search for Off-Diagonal Density Matrix Elements for Atoms in a Supersonic Beam, Richard A. Rubenstein, Al-Amin Dhirani, David A. Kokorowski, Tony D. Roberts, Edward T. Smith, Winthrop W. Smith, Herbert J. Bernstein, Jana Lehner, Subhadeep Gupta, and David E. Pritchard, Phys. Rev. Lett., **82**, 2018-2021, (1999).

#### **Technical reports:**

Basic Atomic Physics, Research Laboratory of Electronics Progress Report, **141**, 211-227, (1998).

**Presentations:**

"Longitudinal Interferometry" at III Adriatico Conference on Quantum Interferometry, Miramare-Trieste, Italy. Mar 1-5, 1999. (Invited talk)

"Longitudinal Interferometry" at 5<sup>th</sup> Workshop on Atom Optics and Atom Interferometry, Westerland, Sylt. Mar 7-11, 1999. (Invited talk)

"Differential Ramsey Interferometry" at 14<sup>th</sup> International Conference on Laser Spectroscopy. Innsbruck, Austria. Jun 7-11, 1999. (Invited talk)

"Atom Interferometry" at AAAS Annual Meeting. Anaheim, CA. Jan 3, 1999 (invited talk)

**Honors, awards, & Prizes:**

Prof. David E. Pritchard – elected member of the National Academy of Sciences

**Number of students supported:** 2 doctoral, 0 females, 0 from under-represented ethnic groups

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